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METHOD FOR ESTIMATING RATIO OF ABSORPTANCE TO EMITTANCE

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METHOD FOR ESTIMATING RATIO OF ABSORPTANCE TO EMITTANCE

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SUMMARY

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A graphical method is presented for estimating the values of the ratio of absorptance to emittance α/ϵ that can be achieved with surfaces having a high degree of spectral selectivity. The ratio of source to surface temperature is the parameter in the graphs. In principle, the results of the calculations presented are general and apply for any source or surface temperature. In practice, the ratios of absorptance to emittance so estimated can be used in radiant-heat-transfer calculations involving space vehicles. In this case α becomes α_s, the total normal absorptance of a surface to solar radiation, and ϵ is the total hemispherical emittance.

Author

INTRODUCTION

In environments where heat transfer to or from a surface is entirely or primarily through radiation, a knowledge of the surface absorptance α and the surface emittance ϵ is necessary for heat-transfer calculations. There are conditions, however, where only the ratio of absorptance to emittance α/ϵ need be known to calculate the temperature or performance of a system; the individual values of α and ϵ need not be used. These are conditions where the internal heat fluxes to or from the surface are either zero or small compared with the external, radiant heat fluxes. The principal example is the space vehicle exposed to sunlight. In this case, α becomes the total directional absorptance of solar radiation α_s. For example, the boiloff loss of cryogenic propellants from a well-insulated tank in space is directly proportional to the ratio α_s/ϵ of the external surface of the tank and is independent of the value of α_s (ref. 1).

Gray surfaces are those for which both the monochromatic absorptance α_λ and the monochromatic emittance ϵ_λ are invariant with wavelength. For perfectly diffuse surfaces, $\alpha_\lambda = \epsilon_\lambda$, and therefore, for gray diffuse surfaces, $\alpha = \alpha_\lambda = \epsilon_\lambda = \epsilon$ and

$\alpha/\epsilon = 1.0$. This is not the case for most materials. Values of α_s/ϵ for metals are greater than unity because their monochromatic absorptance and emittance decrease with increasing wavelength λ (as shown, e.g., in ref. 2). Therefore, α_s is greater for the relatively short wavelength radiation from the Sun than is ϵ for the longer wavelength radiation emitted from the much colder surface. Semiconductors are similar to metals in that their α_s/ϵ is greater than 1. Nonconductors have α_s/ϵ values less than unity because α_λ and ϵ_λ increase with increasing wavelength for this class of compounds.

Considerable effort is now being aimed at producing surfaces having ratios either as high or as low as possible. High surface temperatures result from high values of α_s/ϵ and are most effective in increasing the performance of flat-plate collectors of solar energy (see, e.g., ref. 3). Surfaces having low values for this ratio give low temperatures and might be used, for example, on the previously mentioned cryogenic tanks.

For any given surface with spectral properties described in terms of α_λ as a function of wavelength and for any given source temperature or surface temperature, the values of α, ϵ, and α/ϵ can be calculated. It was observed, however, that a product term $\lambda_c T$ can be used to develop a series of plots from which α/ϵ can be read directly, provided the source is a gray body or a blackbody. The spectral quality of the surface is characterized by λ_c, which is described later; the temperature T may be either the source temperature T_1 or the surface temperature T_2. The ratio T_1/T_2 is a parameter in these plots.

While such curves may be used in estimating the α/ϵ of spectrally selective surfaces, their greatest value may be in estimating the maximum and minimum values of this ratio that may be achieved. These limiting values of α/ϵ can then be used to estimate the ultimate performance of those systems where the internal heat transfer is small relative to that received and radiated from the external surfaces.

Presented herein are figures that can be used to estimate α/ϵ. These figures are based on the temperature of the radiation source (usually the Sun) and on a simplified but realistic description of spectrally selective surfaces.

SYMBOLS

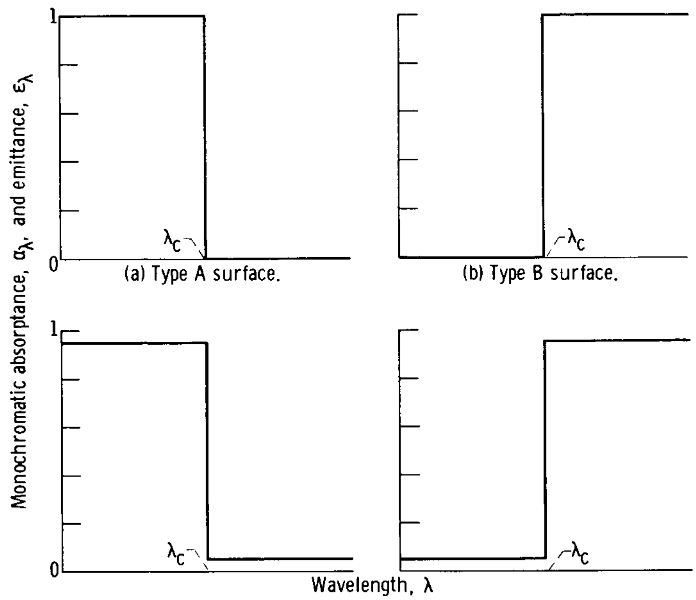
A	area
C	solar radiant flux, W/sq cm
$F_{\lambda,T}$	fraction of total energy radiated by blackbody at temperature T at all wavelengths shorter than λ
T	temperature, $^{\circ}K$

T_1	temperature of radiation source, ^{o}K
T_2	temperature of radiating surface, ^{o}K
$W_{T,B}$	incident radiant flux per unit area from blackbody at temperature T, W/sq cm
$W_{\lambda,T,B}$	incident radiant flux per unit area per unit increment of wavelength from blackbody at temperature T, (W/sq cm)/μ
α	total absorptance of surface
α_s	total directional absorptance to solar radiation
α_λ	monochromatic absorptance
ϵ	total emittance of surface
ϵ_λ	monochromatic emittance
λ	wavelength, μ
λ_c	cutoff wavelength of spectrally selective surface, μ
λ_o	any given wavelength, μ
σ	Stefan-Boltzmann constant, (W/sq cm)/$^{o}K^4$

PROCEDURE AND RESULTS

An ideal spectrally selective surface is one for which the monochromatic absorptance α_λ (and the emittance ϵ_λ) is unity over a span of wavelengths and changes abruptly to zero over the rest of the span. Figure 1 shows this behavior for the two types of ideal spectral surfaces, types A and B. The type A surface with the high value for α_λ and ϵ_λ at short wavelengths is a more powerful absorber for high-temperature radiation than it is an emitter for lower temperature radiation; therefore, α/ϵ is greater than unity. Conversely, for the type B surface α/ϵ is less than unity.

While the type A and B surfaces are ideal in spectral selectivity, it is likely that more practical surfaces are those where a step change in α_λ is between 0.95 and 0.05. These are shown in figure 1 as type C and D surfaces. Type C surfaces with this degree of spectral selectivity have been approached, for example, by coating molybdenum with tantalum oxide. The spectral response of this material is shown in figure 2 as the solid curve (data from ref. 4). Many nonconductors show sharp changes in spectral emittance of the opposite or D type. An example is the spectral emittance curve for magnesium carbonate (from ref. 5) shown as the dashed curve in figure 2.



(c) Type C surface.
(d) Type D surface.

Figure 1. - Absorptance and emittance of ideal spectrally selective surfaces.

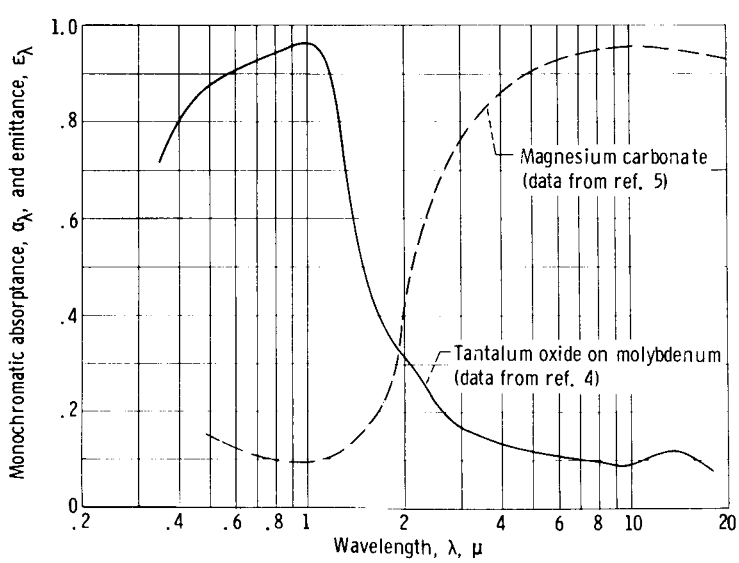


Figure 2. - Absorptance and emittance of two spectrally selective surfaces.

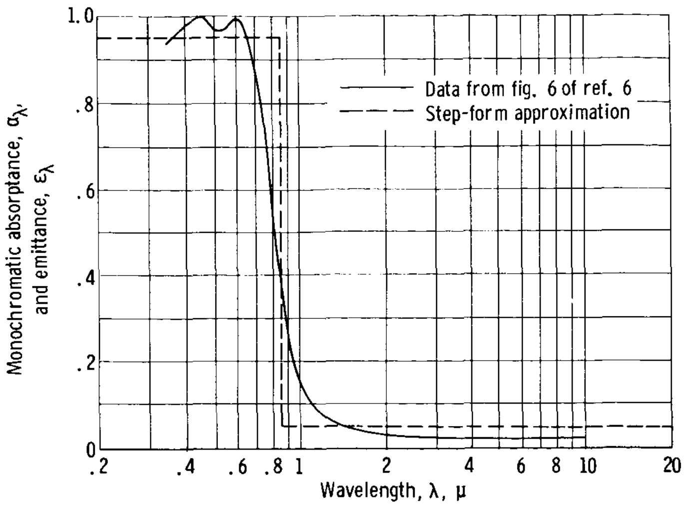


Figure 3. - Spectral absorptance and emittance of copper - germanium - silicon monoxide filter.

The highest degree of spectral selectivity is obtained with multilayer, interference-type surfaces like that shown in figure 3 (data from ref. 6). Figure 6 of reference 6 presents spectral reflectance as a function of wavelength. It was assumed that this filter could be backed by a black surface so that the spectral absorptance or emittance would be equal to 1 minus the spectral reflectance. It is recognized that there will be strong directional effects for such a composite surface, that the total absorptance will vary with the angle of the incident radiation, and that the total emittance (hemispherical) cannot be easily calculated from spectral values. Nevertheless, it is assumed that this approaches a type C surface with an abrupt change in α_λ or ϵ_λ at 0.85 micron.

The spectrally selective surfaces shown in figures 1 to 3 can be characterized by the wavelength at which the spectral absorptance or emittance changes abruptly from a high to a low value. The wavelength of this step change in absorptance or emittance is termed λ_c herein and is used in the subsequent development.

The absorptance of a surface is a function of both the spectral selectivity of the surface and the source temperature or the spectral distribution of the incident flux. If the source is a blackbody, the surface absorptance is given by

$$\alpha = \frac{\int_0^\infty \alpha_\lambda W_{\lambda, T_1, B}\, d\lambda}{W_{T_1, B}} \tag{1}$$

The values of $W_{\lambda, T_1, B}$ and $W_{T_1, B}$ can be calculated for the incident radiation from a source at temperature T_1 from the Planck and Stefan-Boltzmann equations, respectively. In a similar way the emittance of a surface is given by

$$\epsilon = \frac{\int_0^\infty \epsilon_\lambda W_{\lambda, T_2, B}\, d\lambda}{W_{T_2, B}} \tag{2}$$

where the temperature T_2 refers to the temperature of the surface.

However, the fraction of the total energy radiated by a blackbody at all wavelengths shorter than a given value λ_o is a unique function of the product of wavelength and temperature $\lambda_o T$. This fraction is defined as

$$F_{\lambda,T} \equiv \frac{\int_0^{\lambda_o} W_{\lambda,T,B}\, d\lambda}{W_{T,B}}$$

and tables of its values as a function of λT were developed by Lowan and Branch (ref. 7) and can be found in standard references on radiative processes (e.g., ref. 8). The fraction at a wavelength larger than λ_o is then

$$\frac{\int_{\lambda_o}^{\infty} W_{\lambda,T,B}\, d\lambda}{W_{T,B}} = 1 - F_{\lambda,T}$$

If a surface has a high degree of spectral selectivity so that the monochromatic absorptance α_λ is substantially a constant value from $\lambda = 0$ to $\lambda_o = \lambda_c$ and a second constant value from $\lambda_o = \lambda_c$ to $\lambda = \infty$, the α_λ term can be taken outside the integral in equation (1). The absorptance can then be calculated from

$$\alpha = \left(\alpha_{0-\lambda_c} F_{\lambda_c, T}\right) + \alpha_{\lambda_c-\infty}\left(1 - F_{\lambda_c, T}\right) \tag{3}$$

by using values of $F_{\lambda,T}$ as a function of λT taken from tables (e.g., ref. 8). Equation (2) can be similarly modified so that the emittance can be calculated from

$$\epsilon = \left(\epsilon_{0-\lambda_c} F_{\lambda_c, T}\right) + \epsilon_{\lambda_c-\infty}\left(1 - F_{\lambda_c, T}\right) \tag{4}$$

The source temperature is used in determining the absorptance by equation (3), and the surface temperature is used with equation (4) for emittance.

Since $\alpha_{0-\lambda_c} = \epsilon_{0-\lambda_c}$ and $\alpha_{\lambda_c-\infty} = \epsilon_{\lambda_c-\infty}$, numerical values for these quantities

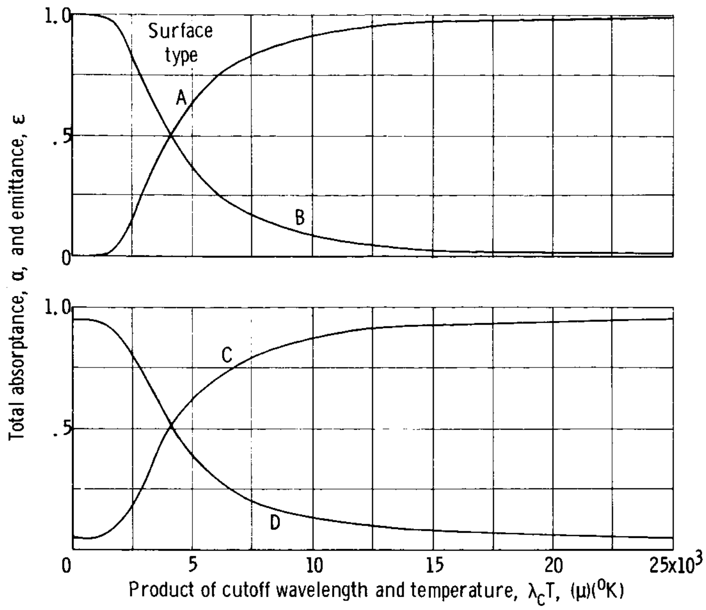


Figure 4. - Total absorptance and emittance for ideal spectrally selective surfaces.

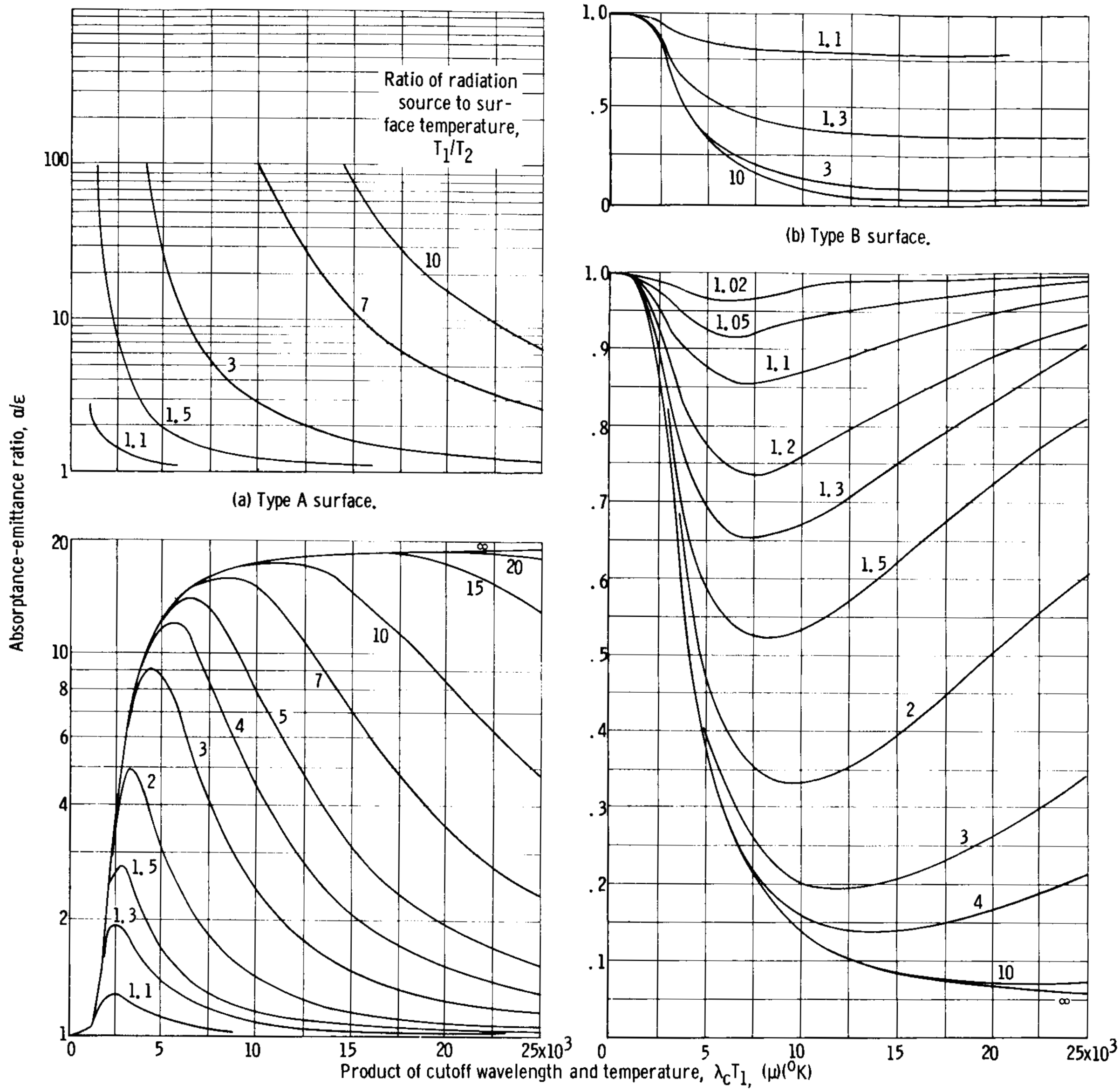
can be used interchangeably in equations (3) and (4).

Equations (3) and (4) have been used to calculate the absorptance or emittance of ideal spectrally selective surfaces for various values of $\lambda_c T$. These are plotted in figure 4 for the four surfaces of figure 1. Figure 4 can be used to estimate α or ϵ for any surface where the monochromatic absorptance and emittance approach the step functions shown in figure 1 and where the source and the surface temperature are known. For example, if the surface shown in figure 3 is assumed to be equivalent to one having $\alpha_\lambda = \epsilon_\lambda = 0.95$ at all wavelengths shorter than 0.85 micron, and $\alpha_\lambda = \epsilon_\lambda = 0.05$ at all wavelengths longer than 0.85 micron (the dotted line in fig. 3), and if the incident radiation is from the Sun or a 6000° K blackbody, then $\lambda_c T_1 = (0.85\ \mu)(6000^\circ\ K) = 5100\ (\mu)(^\circ K)$. Figure 4 gives a total absorptance of 0.63 for these conditions (type C surface). Similarly, if the same surface is at 500° K, the $\lambda_c T_2$ value is 425 $(\mu)(^\circ K)$ and the total emittance value of 0.05 can be read from figure 4 (type C surface). The α/ϵ for this surface and these temperatures is $0.63/0.05 = 12.6$.

The example just given indicates that it is also possible to plot α/ϵ as a function of $\lambda_c T$ by using temperature ratios as parameters. The example of $\alpha/\epsilon = 12.6$ for a temperature ratio T_1/T_2 of $6000/500 = 12.0$ and a $\lambda_c T_1$ of 5100 $(\mu)(^\circ K)$ would be one point in developing the curves. Curves could also be developed based on a $\lambda_c T_2$ of 425 $(\mu)(^\circ K)$ in the preceding example by using the surface rather than the source temperature as the reference value.

Such curves were developed by using the source temperature T_1 in the $\lambda_c T$ term since most of the work in this area is related to sunlit systems where 6000° K can be used as T_1. The alternative of using the surface temperature would be less convenient since the surface temperature is often unknown and may be the quantity that is to be calculated after α/ϵ is established. The surface temperature T_2 must still be estimated to determine the temperature-ratio parameter, but, for a sunlit surface operating below 500° K $(T_1/T_2 > 12)$, the results are relatively insensitive to changes in T_2.

Calculated α/ϵ values are presented in figures 5(a) and (b) as a function of $\lambda_c T_1$ for ideal spectrally selective surfaces, that is, those with a step change in α_λ from



(a) Type A surface.

(b) Type B surface.

(c) Type C surface.

(d) Type D surface.

Figure 5. - Absorptance-emittance ratio for spectrally selective surfaces as function of wavelength-temperature product and temperature ratio.

1.0 to 0.0; T_1/T_2 is the parameter in these curves.

For the type A surface, α/ϵ increases continuously both with decreasing $\lambda_c T_1$ and with increasing T_1/T_2 (fig. 5(a)). Very high values for α/ϵ would be achieved with surfaces having λ_c at short wavelengths so that $\lambda_c T_1$ would be small.

For the type B surface, α/ϵ decreases both with increasing $\lambda_c T_1$ and with increasing T_1/T_2 (fig. 5(b)), and α/ϵ approaches zero as a limit with increasing T_1/T_2.

The results shown in figures 5(a) and (b), however, are largely academic because surfaces with this degree of spectral selectivity are not presently attainable. A more realistic degree of spectral selectivity is seen in the type C and D surfaces, where α_λ and ϵ_λ change from 0.95 to 0.05. Calculated values for α/ϵ are presented in figures 5(c) and (d) for these types of surfaces.

When the results for type A and C surfaces (figs. 5(a) and (c)) are compared, it can be seen that curves of quite different shape are obtained. For the type C surfaces α/ϵ does not increase continuously with decreasing $\lambda_c T$ but reaches a maximum value for each temperature ratio. At lower temperature ratios these maximums are a quite sharp function of $\lambda_c T_1$ and show that there is an optimum value of λ_c for any given source temperature. Figure 5(c) can be used, therefore, as a guide in developing a surface coating for any particular mission. At higher temperature ratios, the maximum α/ϵ is a less sensitive function of $\lambda_c T_1$.

The theoretical upper limit of α/ϵ that can be achieved with a type C surface is 19.0, and this only for very high temperature ratios and large values of $\lambda_c T_1$ beyond those shown in figure 5(c). The practical upper limit is about 18, as shown for the range of $\lambda_c T_1$ and T_1/T_2 encompassed by this figure.

The type D surface (fig. 5(d)) also gives curves quite differently shaped from those for the ideal type B surface of figure 5(b). Minimum values of α/ϵ are shown as a function of $\lambda_c T$, and these minimums are sharpest at low values of T_1/T_2. The lowest α/ϵ possible for a type D surface is 0.053, and this only for $\lambda_c T_1$ greater than that shown in figure 5(d). A more reasonable lower limit is about 0.070, as shown in this figure.

EXAMPLES

The following cases are presented as examples of the use of the curves presented herein. Figures 5(c) and (d) are used in these illustrations since they are based on spectrally selective surfaces that may be attained in practice.

Case I. - What are the maximum and minimum values of α_s/ϵ that may be achieved for the sunlit surface of a space vehicle at the orbit distance of the Earth from the Sun? The surface temperature will be about 300° K, so that the temperature ratio will be 6000/300 or 20. The maximum α_s/ϵ therefore will be about 18 (fig. 5(c)), and the minimum about 0.07 (fig. 5(d)). In this case it makes little difference whether the vehicle temperature is below 300° K ($T_1/T_2 > 20$) or as high as 600° K ($T_1/T_2 = 10$); substantially the same limiting values of α_s/ϵ will be obtained.

Case II. - Similarly, what are the maximum and minimum values of α/ϵ for surfaces where the temperature ratio is 1.1? An example might be a relatively low temperature experiment operating in a hard vacuum with small temperature differences between adjacent surfaces. In this case the maximum and minimum α/ϵ may be 1.3 and 0.85, respectively, from figures 5(c) and (d).

Case III. - What is the minimum α_s/ϵ and the minimum temperature that may be achieved for a spherical body at 0.1 astronomical unit (Earth orbital distance) from the Sun? If it is assumed that the body is isothermal and that there is no heat source other than the Sun, the equilibrium temperature can be calculated from

$$T_2 = \left(\frac{C}{4\sigma} \frac{\alpha_s}{\epsilon}\right)^{1/4} \tag{5}$$

where C, the solar flux, is 13.5 watts per square centimeter at 0.1 astronomical unit and the constant 4 is due to the radiating surface area of a sphere being four times greater than its projected or absorbing area. Equation (5) is a simple derivation for the conditions of equal flux absorption and reradiation, where $C\alpha_s A = \epsilon\sigma T_2^4 4A$. The temperature for a gray body ($\alpha_s/\epsilon = 1.0$) is 878° K from equation (5) but would be considerably less for a low α_s/ϵ surface; 600° K can be used for the first approximation. For a 600° K surface the temperature ratio will be 10, and figure 5(d) indicates that an α_s/ϵ of 0.07 may be achieved. Inserting this value in equation (5) gives a temperature of 451° K. No further iteration is required since the minimum α_s/ϵ taken from figure 5(d) for this temperature ratio ($T_1/T_2 = 13$) is substantially the same as that for the first approximation, where $T_1/T_2 = 10$.

Case IV. - What is the maximum α_s/ϵ and the maximum temperature that may be achieved under the conditions of case III? As a first approximation, assume a temperature of 1000° K so that $T_1/T_2 = 6$ and the maximum α_s/ϵ is about 14 (fig. 5(c)). This value of α_s/ϵ results in a temperature of 1700° K and a temperature ratio of 3.5. The second approximation must start with a temperature ratio between 3.5 and 6.0 but much closer to the lower value. A ratio of 3.75 is taken where the maximum α_s/ϵ is approximately 11.0. This approximation results in a temperature of 1600° K or a temperature ratio of 3.75. No further iterations are required.

Case V. - At what wavelength should the monochromatic absorptance or emittance of the surface change from a high to a low value to achieve the maximum α_s/ϵ desired under the conditions of case IV? The temperature ratio was found to be about 3.75 in case IV, and figure 5(c) shows that the maximum α_s/ϵ is obtained at a $\lambda_c T_1$ value of about 5500 (μ)(°K). Since T_1 is 6000° K, the wavelength λ_c is 0.917 micron. In other words, a spectrally selective surface should be sought for which the monochromatic absorptance or emittance is as high as possible at wavelengths less than 0.9 micron and as low as possible at longer wavelengths.

TABLE I. - COMPARISON OF MEASURED AND ESTIMATED ABSORPTANCE-EMITTANCE RATIOS

Surface temperature, T_2, ^{o}K	Ratio of source to surface temperature, T_1/T_2	Data from ref. 4			α_s/ϵ predicted from fig. 5(c)
		Total absorptance, α_s	Total emittance, ϵ	α_s/ϵ	
298	20	0.83	0.051	16.3	17
533	11.2	.79	.058	13.6	17
819	7.3	.68	.078	8.7	16

COMPARISON WITH PRESENT STATE OF THE ART

Figures 5(c) and (d) show the α/ϵ values that can be obtained with various ratios of source to surface temperature. These are based on a somewhat idealized description of surface spectral selectivity, and it is interesting to compare these predictions with what has been achieved to date. While no exhaustive literature search has been made, data are available from two recent reports that indicate the present state of the art in this regard.

Highest values of α/ϵ are obtained by coating a good reflector (a polished metal) with a selective absorber for short-wavelength radiation, for example, by coating molybdenum with tantalum oxide (see solid curve in fig. 2).

Solar absorptance and emittance data are given for several surface temperatures in reference 4 for tantalum oxide on molybdenum. These are listed in table I, and α_s/ϵ values are compared with those predicted by the present analysis. The source (Sun) temperature was taken as 6000^{o} K, λ_c as 1.5 microns, and $\lambda_c T_1$ as 9000 $(\mu)(^{o}K)$.

It can be seen that the predicted α_s/ϵ closely approaches the experimental value at high temperature ratios. At the lower temperature ratios (higher surface temperatures), however, the predicted values are well above those determined experimentally. The difference is largely due to a decrease in α_λ at the shorter wavelengths for this material when its temperature is raised from room temperature to 819^{o} K. These data are not shown herein but are clearly shown in figure 12 of reference 4. The surface therefore falls short of being a type C surface at high temperatures in that α_λ is less than 0.95 at short wavelengths.

As for surfaces with very low α_s/ϵ values, total absorptance and emittance were not given for the magnesium carbonate used in figure 2 as an example of a type D material. An α_s/ϵ of 0.17, however, has been reported (ref. 9) for a surface painted with calcium silicate pigment in a sodium silicate vehicle. The latter painted surface should have a spectral response similar to that of magnesium carbonate in that α_λ should be low at shorter wavelengths. If the paint is assumed to have a λ_c of 2 microns, the value for magnesium carbonate, then $\lambda_c T_1 = 12\ 000\ (\mu)(^{o}K)$. Figure 5(d) predicts an α_s/ϵ of 0.11 for temperature ratios of 10 or greater. This predicted value for α_s/ϵ is somewhat lower than the experimental value of 0.17 and suggests that further work is needed to develop a surface to achieve minimum α_s/ϵ values.

To this point the discussion has largely been concerned with the possibilities of achieving a high degree of spectral selectivity through having α_λ or ϵ_λ at high values over one range of wavelengths and at low values over another. The requirements for having a sharp break from one value to another have not been discussed. The importance of this latter factor depends strongly on the temperature ratio of the system, as shown in the following examples.

Consider a system with a temperature ratio T_1/T_2 of 20. At this ratio, 98 percent of the energy radiated from a black or gray source at T_1 is at λT_1 less than 17.7×10^3 $(\mu)(^{\circ}K)$ and 98 percent of the energy radiated from a similar surface at T_2 is at λT_1 greater than 32.0×10^3 $(\mu)(^{\circ}K)$. For λT_1 values between 17.7×10^3 and 32.0×10^3 $(\mu)(^{\circ}K)$ there is very little energy radiated from either source or surface. Therefore, the values for α_λ and ϵ_λ that a surface has in this range have very little influence on α, ϵ, or α/ϵ. The surface can have a sharp break at the λ_c that gives a $\lambda_c T_1$ product anywhere between 17.7×10^3 and 32.0×10^3 $(\mu)(^{\circ}K)$, or there can be a slow transition between high and low values of α_λ in this range without significantly changing the performance of the surface.

If the temperature ratio is reduced to 10, 98 percent of the source energy is still at λT_1 less than 17.7×10^3 $(\mu)(^{\circ}K)$, but 3.5 percent of the energy of the surface is also found below this value. Therefore, at $T_1/T_2 = 10$, there is a small overlap in the spectral distribution from source and surface, and this overlap increases as the temperature ratio decreases. At the lower temperature ratios it becomes increasingly important to have λ_c at the proper wavelength and for α_λ to change value as abruptly as possible.

The shape of the curves in figures 5(c) and (d) give quantitative confirmation to the preceding statements. Sharp maximums and minimums are shown for the lower values of T_1/T_2, but at the higher temperature ratios these maximums and minimums are a less sensitive function of λT_1.

CONCLUDING REMARKS

It has been shown that the product of λ_c, a term characterizing the spectral quality of a surface, and T, the temperature of a black or gray radiation source, can be used to develop a series of completely general curves from which values for the ratio of absorptance to emittance α/ϵ can be read directly. Such curves were developed for surfaces with two degrees of spectral selectivity, those representing a theoretical limit and those that may be within reach experimentally.

The latter curves indicate that the maximum α/ϵ that is likely to be attained is about 18, and the minimum is about 0.070. These maximums and minimums are attainable only at high values of the ratio of radiation source to surface temperature. At lower values of this temperature ratio, α/ϵ will be much closer to unity.

Examples are given to show both the use of these curves and the degree to which predicted values have been approached in practice.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 12, 1965.

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